LAMETA
Laboratoire Montpelliérain d'Economie Théorique et Appliquée

UMR
Unité Mixte de Recherche

DOCUMENT de RECHERCHE

« International Environmental Cooperation : A New Eye on the Greenhouse Gases Emissions' Control »

Mélanie HEUGUES

DR n°2009-04

Faculté de Sciences Economiques - Espace Richter
Avenue de la Mer - Site de Richter C.S. 79606
34960 MONTPELLIER CEDEX 2
Tél: 33(0)467158495 Fax: 33(0)467158467
E-mail: lameta@lameta.univ-montp1.fr

Université Montpellier 1 · agro Montpellier Ecole Nationale Supérieure Agronomique · CNRS Centre National de la Recherche Scientifique · INRA

International Environmental Cooperation:
A New Eye on the Greenhouse Gases Emissions' Control

Mélanie HEUGUES[1]

Abstract

We examine the formation of International Environmental Agreements (IEAs) modelled as a two-stage non cooperative game. Following Barrett (1994), Finus (2001) and Diamantoudi & al. (2006) and filling out their approach, we analyse the level of cooperation that can be reach when countries' strategies are complementary. We find that when strategies exhibit weak complementarities, the unique stable agreement can consist of half the countries involved in the negotiation and thus, without any form of commitment, linkage or transfers between countries. These results, established analytically, strongly contrast with those of the previous authors and are a lot more optimistic. Nonetheless, even if the incentives to free-ride are less strong, we do not observe the formation of the "grand" coalition: not all the countries sign the agreement. We also provide some results of comparative static. We analyse, for example, the level of cooperation which only depends on the number of countries concerned with the problem of climate change and on the perception they have of its seriousness.

Key Words: Non-cooperative game theory, International environmental agreements, Strategic complementarities, Coalition formation
JEL Codes: D62, Q28

[1] LAMETA, University of Montpellier. Mail: heugues@lameta.univ-montp1.fr

1. Introduction

The problem of climate change belongs to the class of global environmental problems in the sense that damages a country bears, do not depend on its own emissions but on aggregate emissions: every country emits greenhouse gases into the atmosphere and every country will be affected by the climate change caused by the accumulation of these gases. Even if the impacts of global warming can be sustained differently by each country, environmental changes only depend on world emissions. The main reasons why the control of greenhouse gas emissions (afterwards GHG emissions) now covers an international dimension are the following: (i) once emitted, GHG concentrations become quickly and rather uniform around the world, (ii) as a consequence of trade globalization of these last 50 years, the sources of pollution come from economic activities which are less and less geographically bounded and (iii) national environmental policies are increasingly interdependent. Consequently, the economic regulation of the environment has to be undertaken at an international level[2]. Empirical observations from the last twenty years strongly support this claim. Taking into account the reality of global warming and of the responsibility of human activities on climate imbalances, some governments have begun environmental policies to curb their GHG emissions. The Kyoto Protocol, in effect since 2005, is the most recent example of an international coordination to take action in the matter of climate change.

However, the main source of failure of the international system is States' sovereignty. In our realm, there is no supranational authority to enforce arrangements between countries. When environmental problems are global, involving all countries, each of them has to decide voluntarily to provide or not the public good 'Environment', i.e to reduce its GHG emissions. It also means that International Environmental Agreements (IEA) have to be self-enforcing in the sense that they are immune to deviation by the countries involved. Theoretical models developed until recently try to explain the emergence of cooperation between countries when they are subject to strong environmental externalities. An important result of this literature is that cooperation emerges even in a non-cooperative setting (Carraro & Siniscalco, 1991; Barrett, 1994; Finus & Rundshagen, 1998; Diamantoudi & al., 2006 among others). These results are based on non-cooperative game theory and more particularly on endogenous coalitions' formation theory with spillovers. Game theory is particularly appropriate to

[2] See Barrett (2005) for an overview of the type of environmental problems IEAs are meant to address.

account for strategic interdependence between agents. In our framework, the literature shows that there exists a stable coalition, as defined in industrial organization by D'Aspremont & al. (1983) and extended to IEA (Barrett, 1994; Bauer, 1992; Hoel, 1992). In other words, a subset of countries involved in the negotiation find beneficial to jointly diminish their emissions, meaning that it is in their self-interest; the agreement is self-enforcing. However the equilibrium number of signatories is in general rather small with respect to the number of countries concerned with the environmental problem. No more than four countries will form the stable coalition without regard on the number of countries involved in the negotiation (Diamantoudi et al., 2006). Hence, the impacts of the actions undertaken remain limited and do not allow restoring the global optimum.

Actually it turns out that the robustness of this result on the emergence of environmental cooperation without any trigger or stick mechanisms is based on one assumption which appears in most of the studies on international environment but is seldom discussed: the pattern of interdependence among countries. This latter is described by the slope of the best-reply functions, and it is fundamental for understanding the effectiveness of cooperative and non-cooperative emission control (Carraro and Siniscalco, 1991)[3]. Whereas they are derived from the most general form of the payoff function used by the literature on IEAs, the results discussed above suppose that countries' strategy are substitutable[4].

In this paper we are looking for what happens when strategies become complementary. This assumption means that, if a country increases its emissions, the others will have a positive incentive to do the same. This idea is meaningful if we look at the current economies of developed counties and their political and trade interconnections. The formation of free trade areas (regionalization) in Europe, Asia or America have led to a boom of trade between countries belonging to these blocks. Obviously, if the United-States falls in a recessionary period tomorrow, the level of activities of its trade partners will fall as well.

---

[4] Carraro and Siniscalco (1991) already underlined this idea, but confined their study to the case where the slope of the best-reply functions are negative. They find that the more negative it is, the larger the incentive to deviate from any coalition.

[4] For an overview of assumptions and results of game theoretical analyses of IEAs see Finus (2001 and 2003a).

Going further into prior findings, we analyse in this paper the level of cooperation that can be reach when countries' strategies are complementary. The countries, which are the decision-making units, are interdependent in the sense that their economic activities are more and more connected and integrated. The study of coalition formation under strategic complementarities has already provided some interesting results in considering the case of the spread of catalytic converters in automobiles (Heal, 1993; Barrett, 2003). Under discrete policy choices and multiplicity of equilibria, these authors find that the challenge for countries concerned with the protection of the environment is not anymore how to sustain full cooperation? but rather how to get to the preferred equilibrium? In other words, the existence of reinforcement effects between countries' strategies turns the initial preoccupation into a coordination problem. Therefore, with a threshold constraint, an IEA may help to coordinate States' behaviour such that the welfare-superior equilibrium is sustained.

What distinguish our findings to previous is that, we do not consider perfect complementarities between countries. In the tradition of the first models, the question always is: how many countries will sign the agreement? Thereby, in this paper, we choose to consider the problem of international pollution control in a similar way to Diamantoudi & al. (2006) with quadratic benefit and damage functions. One main difference is the specific functional forms which exhibits strategic complementarities. So, we study the incentives schemes of sovereign countries which sign a treaty. The equilibrium number of countries participating in an IEA is derived by applying the internal and external stability concept borrowed from the oligopoly literature. We show that, under these assumptions, cooperation is largely greater. Nonetheless, all the results depend on the number of countries involved in the negotiation and their perception of environmental damages with respect to the benefits of their GHG emissions. Moreover, even if an agreement will always be signed, it will never be the "grand coalition".

The paper is organised as follow. In section 2, the fundamental functions and assumptions of the game are defined. In the third section, we derive the non-cooperative and the full cooperative outcomes. These solutions are used as a benchmark to analyse signatories' and non-signatories' behaviour. Finally, we establish analytically the size of the stable agreement, i.e. the level of cooperation that can be reached by the countries under strategic complementarities. The last section concludes. The proofs of all results are given in the appendix.

2. Fundamental functions and assumptions of the emission game

We consider *n* symmetric countries with $N = \{1, ..., n\}$. Linked to economic activities, each of them emits greenhouse gases (GHGs), $x_i \geq 0$, that mix uniformly in the atmosphere. In its most general form, the payoff function of country i, f_i, is expressed as the difference between the benefits of emissions, $B_i(x_i)$, and the damages linked to global emissions, $D_i(\sum_{i \in N} x_i)$. Then, f_i can be written:

$$f_i = B_i(x_i) - D_i(\sum_j x_j), \forall i, j \in N .$$

Emissions are viewed as an output of the production and consumption of goods from which benefits are derived, while the payoff function describes the welfare implication from emissions at an aggregate level. Even if the impacts of global warming can be supported differently by each country, environmental changes only depend on world emissions. Hence, the damage function of the country under consideration does not depend on its own contribution but rather on the sum of the emission levels supplied by all countries. So, emissions in a country generate an externality causing environmental damage in this country but also in the other countries.

Since the countries are assumed to be identical, we drop the subscripts from the functions. Moreover, we will note *x*, *y* and *z* respectively the emission level of the country under consideration, the aggregate emission level of the $(n - 1)$ other countries, and the global emission level, i.e., $z = x + y$.
We will assume that the benefit function is increasing in the level of emissions, i.e. $B'(x_i) > 0$. Similarly, given that emissions disperse uniformly in the atmosphere, the damage function is supposed to increase in the global emissions *z*, i.e. $D'(\cdot) > 0$ over R_+.

For each country, we assume hereafter the following specific benefit and damage functions:

$B(x) = b(x-1)^{1/2}$, with *b* a positive benefit parameter, and

$D(x+y) = c(x+y)^{1/2}$, with *c* a positive cost parameter.

In the current literature parameters b and c are usually introduce to analyse the relative impact of cost of emissions compared to benefit. Parameter b is often interpreted as an opportunity cost of abatement whereas in Endres (1997) parameter c is interpreted as the environmental awareness of the society of a country. Particular attention will be given to the effect of a change in these parameters on the success and stability of an IEA.

Each of these functions is increasing in the individual emission level but at a decreasing rate. We assume a concave damage function because when damages only depend on aggregate emissions, it's the only way for payoff functions to exhibit strategic complementarities.

For a country, the form of the payoff function is then:

$$f(x, y) = b(x-1)^{1/2} - c(x+y)^{1/2} \text{, with } 1 \leq x \leq \mathrm{K},$$

With K accounting for a capacity constraint. It means that a country cannot produce infinitely GHG's emissions or that its economic activities are bounded. Similarly, notice that our function set forth a lower bound on emissions in the sense that a country cannot reduce its economic activities under some level.

In the following, each country is supposed to maximise its payoff function to determine its level of emissions. We first consider the non-cooperative and the full cooperative cases. They are next used as a benchmark to study the endogenous formation of an environmental agreement.

3. The non-cooperative and full cooperative outcomes

3.1. The pure non cooperative case

In the pure non-cooperative case each country chooses its emission level taking the other countries' emission as given:

$$Max_{\,x \geq 0}\, f(x, y) = b(x-1)^{1/2} - c(x+y)^{1/2}.$$

For the country under consideration the necessary condition leads to the following reaction function:

$$x(y) = \frac{\gamma^2 + y}{\gamma^2 - 1} \text{ with } \gamma = \frac{c}{b}.$$

In what follows, $\gamma = c / b$ is defined as the cost/benefit ratio of GHG emissions. It represents the perception that countries have of environmental damages in comparison with the benefits they obtain from their emissions. Given the assumption of identical countries, $y = (n-1)x$. The emission levels for a country and the global emissions in the non-cooperative case are respectively:

$$x_{nc} = \frac{\gamma^2}{\gamma^2 - n},$$

$$z_{nc} = nx_{nc} = \frac{n\gamma^2}{\gamma^2 - n}.$$

The constraint on the emission levels is observed for all n when $\gamma^2 > \frac{nK}{K-1}$.

Given equilibrium emission levels, the shape of the payoff function of a country in the non-cooperative case is:

$$f_{nc} = \frac{bn^{1/2}(1-\gamma^2)}{(\gamma^2 - n)^{1/2}}.$$

From our assumptions on the payoff functions and the solutions of the maximisation problem, we can establish a preliminary result.

Result 1:

Under our assumptions, countries' strategies exhibit weak complementarities. It follows that:

(i) Individual and aggregate equilibrium emissions levels, x_{nc} and z_{nc} are increasing in n and decreasing in γ;

(ii) The equilibrium payoff of each country is decreasing in n and increasing in γ until $\overline{\gamma} = (2n-1)^{1/2}$; beyond it decreases in γ.

When countries' strategies exhibit complementarities it means that, if a country increases its levels of production and consumption and thus its level of emissions, the others have a positive incentive to do the same. Hence, the marginal utility a country gets from its emissions is increasing in the level of emissions of the other countries.

Moreover, when considering countries as trade partners, the larger is n, the more a country will increase its trade relationships and thus its economic activities. However it also means that the level of emissions of each country will be increasing in the number of countries involved. As a result of the non-cooperative case, the larger is the number of countries concerned with the environmental problem, the greater the individual and aggregate equilibrium emissions levels and the higher the marginal utility a country derived from its emissions. This result is immediately linked to strategic complementarities between countries. Furthermore, there is nothing new in saying that the more the damages are perceived seriously compared to the benefits of emissions, the lower the equilibrium emission level of a country. In other words, the marginal utility of emissions of each country is decreasing in the cost/benefit ratio. Therefore, referring to the second point of result 1, as soon as the perception of damages is not too strong ($\gamma < \overline{\gamma}$), equilibrium payoffs are increasing in the perception of damages. The existence of γ restrains the emission level of each country and then the importance of externalities. The larger is γ, the more the levels of emissions are contained and the higher the equilibrium payoffs. Beyond the threshold $\overline{\gamma}$, what happens is that damages are perceived so seriously that all countries emit as less as possible and cannot reduce their emission level as much as in the prior case. Hence, the abatement effort does not suffice to balance the importance of the externalities. Yet countries have no choice except to suffer the losses linked to environmental damages without having a real impact on it.

Finally the last point is linked to the fact that the game is a game with negative externality, and countries, when choosing their emission level, do not take into account the impact of their choice on the other countries. This phenomenon is amplified by the fact that countries' strategies are complementary: if a country increases its emissions, the others have an incentive to increase their own emissions. So, at the Nash equilibrium there is an increasing incentive to have greater emissions. Thus, the larger is n, the greater are the environmental externalities and the lower are the equilibrium utilities. In the same way, the larger is n, the higher will be the global emissions and the more severe the environmental problem. In this setting, countries should be more incline to cooperate. Before studying endogenous cooperation between countries, we now present what happens in the full cooperative case. In other words, we analyse the situation when each country takes into account the negative externality it imposes upon other countries.

3.2. The full cooperative case

In the full cooperative case, we assume that the whole countries maximize their joint payoff. Formally we solve the following maximization problem:

$$Max_{z\geq 0}\, n\left(b(\frac{z}{n}-1)^{1/2} - cz^{1/2} \right).$$

The necessary condition leads to the following aggregate emission level of full cooperation:

$$z_c = \frac{n^2\gamma^2}{n\gamma^2 - 1}.$$

Since each country contributes the same fraction of total emissions, the per-country emission level is:

$$x_c = \frac{z_c}{n} = \frac{n\gamma^2}{n\gamma^2 - 1}.$$

Given equilibrium emission levels, the shape of the payoff function for each country in the full cooperative case is:

$$f_c = -b(n\gamma^2 - 1)^{1/2}.$$

As in the non-cooperative case, we establish the same kind of comparative static results when all countries cooperate (result 2) and then we compare the equilibrium emission levels and equilibrium payoffs with the non-cooperative outcomes (result 3).

Result 2:

In the full cooperative case, we find that:

(i) Individual equilibrium emission level, x_c is decreasing in *n* whereas aggregate equilibrium emission level, z_c is increasing in *n*;

(ii) Individual and aggregate equilibrium emission levels, x_c and z_c are decreasing in γ;

(iii) The equilibrium payoff of each country is decreasing in *n* and in γ.

Under our assumptions we find that when all countries cooperate, individual emission levels are decreasing in *n*. This observation is linked to the fact that the game is of negative externalities. When cooperating, countries take into account the negative impact of their emissions on the other countries. The larger is *n*, the larger is the scope of emissions and the lower will be the individual emissions. In other words, countries have to take into account *n* times the environmental damages linked with their emissions instead of one time. Nonetheless, global emissions keep on increasing in the number of countries concerned with the environmental problem. Consequently, equilibrium payoffs are decreasing in *n*. However, contrary to the non-cooperative case, it is because abatement efforts are increasing in the number of countries concerned with the environmental problem.

As previously individual and aggregate emission levels are decreasing in the cost/benefit ratio, i.e. the stronger is the perception of the seriousness of the environmental damages, the more countries will reduce their individual emission level. The payoff of full cooperation is decreasing in γ because countries, in cooperating, do their maximum to reduce their impact on the environment. The stronger is their perception of the damages compared with the benefits of emissions, the lower is their utility.

Before contrasting emission levels and payoffs under full cooperation with the non-cooperative outcome, we define the indexes I_1 and I_2. The first one corresponds to the relative difference between global emissions in the Nash equilibrium and in the social optimum. It defines, in relative terms, the 'degree of externality' (Finus, 2001). The latter index states the relative difference between joint payoffs in the social optimum and in the Nash equilibrium[5]:

$$I_1 = \frac{(z_{nc} - z_c)}{z_{nc}},$$

$$I_2 = \frac{(\Sigma f_c - \Sigma f_{nc})}{\Sigma f_c} = \frac{(nf_c - nf_{nc})}{nf_c}.$$

Result 3:

We can assess the three following points:

(i) Individual and aggregate equilibrium emission levels under full cooperation, x_c and z_c are such that $x_c < x_{nc}$ and $z_c < z_{nc}$;

(ii) Equilibrium payoffs are such that $f_c > f_{nc}$;

(iii) I_1 is increasing in n and decreasing in γ whereas we find the reverse result for I_2.

We find the standard results of games exhibiting negative externalities: countries are better off under full cooperation than in the non-cooperative setting. As each country takes into account

[5] The second index in terms of payoffs can be defined because all payoffs for all countries and in all cases are of the same sign.

the negative impact of its emissions on the others, the country reduces its individual emission with respect to the non-cooperative outcome. Globally, aggregate emissions also fall. Each wins of such a strategy.

The last point means that, the larger the number of countries which suffer from the global externality and the lower the cost/benefit ratio of emissions, the more important it is to reach a cooperative agreement. The first result is characteristic of the provision of public goods. The latter indicates that emission reduction is particularly attractive if the perception of damages is not to strong with respect to the benefits of emissions. In interpreting parameter b as the opportunity cost of abatement, the bigger is b relative to environmental costs (γ is low) the higher will be the emissions in the non-cooperative outcome and the more inefficient will be the situation from the global society's point of view. In contrast, if environmental damages are very high, only moderate emission reductions are advisable from a global perspective. Cooperation is then less attractive because individual emissions are already as low as possible. Hence, only moderate emission reductions can be reached.

Relatively to the second index, gains linked to cooperation are higher, the number of countries concerned with the environmental problem is not too large and the stronger is the perception of damages. In other words, linked to the cost/benefit ratio, cooperation will pay less if opportunity costs of abatement are high or environmental awareness is low (γ is low). Hence, the higher will be the 'degree of externality' the lower will be the relative difference in terms of payoffs (individual actions of abatement are taken more easily when the 'degree of externality' is increasing).

For any n and γ, the full cooperative outcome is the best possible cooperative solution. However, in the realm of one stage game with simultaneous play, each country has an incentive to take advantage of the agreement and to free ride on the emission reduction achieved by the countries complying with the agreement. Thereby each country earns a lot more in deviating unilaterally, i.e. it benefits of a better environment without paying the cost.

In what follows we consider the two-stage framework. In a first step each country decides to be a signatory or a non-signatory. In a second step, they play the emission game. In doing so, the incentive to free ride on the coalition's cooperating efforts may be offset by the adjustment of the coalition's emissions upon a member's deviation.

4. The endogenous coalition formation game

In this section, we analyse the emergence of an IEA as the equilibrium of a two-stage game. In the first stage, countries choose independently and simultaneously whether to join an agreement or to remain a non-signatory. Given the option chosen in the first stage, signatories and non-signatories then decide in a second stage of their emission levels. Hence we restrict our attention to the formation of only one, non-trivial[6], coalition. It's assumed that countries forming an IEA coordinate their policies by jointly maximising the aggregate welfare of the coalition and given the behaviour of non-signatories. Given the assumption of symmetric countries, we assume that signatories agree on a symmetric abatement scheme which implies equal payoffs. In contrast, each non-signatory behaves non-cooperatively and chooses its emission level independently, i.e., given the behaviour of signatories and the behaviour of the other non-signatories. Let $S \subset N$ the set of countries that sign an agreement and *N\S* the set of those who do not. We note $|S| = s$ the size of the coalition, x_s the emission level of a signatory while the total emission generated by the coalition is $X_s = sx_s$. Similarly each non-signatory country emits x_{ns} yielding a total emission level $X_{ns} = (n-s)x_{ns}$. Finally, we assume that players choose their strategies in both stages simultaneously[7].

The next two sub-sections solve the two-stage game by backward induction. The equilibrium emission levels of the second stage are determined first, given the number of signatories, *s*.

4.1. Signatory and non-signatory behaviours in the emission game

Signatories are assumed to act collectively rather than independently. Particularly, they choose the emission level that maximises their aggregate payoff. Notice that, in that case, the damages are a function of both signatories' emissions and non-signatories' emissions. Formally, signatories solve the following maximization problem:

$$Max_{\ xs \geq 0}\, s\left(b(x_s - 1)^{1/2} - c(sx_s + (n-s)x_{ns})^{1/2}\right).$$

The necessary condition leads to the following best response function:

$$x_s(x_{ns}) = \frac{\gamma^2 s^2 + (n-s)x_{ns}}{\gamma^2 s - 1}.$$

[6] A non-trivial coalition is a coalition of at least two members.

[7] This assumption is referred as the *Nash-Cournot assumption* and is in line with the works of Carraro and Siniscalco, 1991; Bauer, 1992; Hoel, 1992. For an alternative assumption, see Barrett 1994 and Finus, 2001.

To determine completely the emission level of the coalition with respect to its size, we have to solve the maximisation problem of a non-signatory.

A non-signatory choose its own emission level, x_i, given the emission levels of the s signatories and of the *(n – s - 1)* other non-signatories. Formally, a non-signatory solves the following problem:

$$Max_{xi\geq 0}\, s\left(b(x_i-1)^{1/2}-c(sx_s+(n-s-1)x_{ns}+x_i)^{1/2}\right).$$

The necessary condition leads to the following best response function:

$$x_i(x_s, x_{ns}) = \frac{\gamma^2 + sx_s + (n-s-1)x_{ns}}{\gamma^2 - 1}.$$

This reaction function is a function of both the emission levels of the signatories and of the other non-signatories. By symmetry, all non-signatories will play the same equilibrium emission level. So, we can establish the emission level of a non-signatory, x_{ns}, as a function of the emission level of the coalition:

$$x_{ns} = (n-s)x_i,$$

$$x_{ns}(x_s) = \frac{\gamma^2 + sx_s}{\gamma^2 - n + s}.$$

The intersection of both best-response functions leads to the following equilibrium emission levels, respectively of a signatory and of a non-signatory:

$$x_s = 1 + \frac{n}{s^2(\gamma^2 - n + s) - s},$$

$$x_{ns} = 1 + \frac{ns}{s(\gamma^2 - n + s) - 1}.$$

The aggregate emission level $z_T = sx_s + (n-s)x_{ns}$ is:

$$z_T = \frac{ns\gamma^2}{s(\gamma^2 - n + s) - 1}.$$

For any n, $s \geq 1$ and γ the equilibrium emission levels are positive and belong to the feasible action set before-defined. To determine the welfare levels of signatories and non-signatories for any given s, we substitute the equilibrium emission levels x_s, x_{ns} and z_T into the corresponding payoff functions. The shapes of the payoff functions, respectively of a signatory and of a non-signatory, are:

$$f_s = \frac{bn^{1/2}(1 - s\gamma^2)}{[s^2(\gamma^2 - n + s) - s]^{1/2}},$$

$$f_{ns} = \frac{b(ns)^{1/2}(1 - \gamma^2)}{[s(\gamma^2 - n + s) - 1]^{1/2}}.$$

From these last equilibrium outcomes, we can establish the following result:

Result 4:

The analysis of the outcomes of the second-stage emission game leads to the following points:

(i) For any s and n, emission level of a signatory will always be below the emission level of a non-signatory, but both reduce their emissions compared with the non-cooperative outcome;

(ii) The payoff of a signatory is always below the one of a non-signatory: $f_s < f_{ns}$, but the difference is decreasing in the number of cooperating countries;

(iii) The larger is the coalition s, the lower the individual emission levels, x_s and x_{ns}, and so, the lower the global emissions z_T;

(iv) Both type of payoff function are increasing in the number of signatories, s.

To understand this result, notice that we are in a mid-case between non-cooperation and full cooperation. The full-cooperative and the pure non-cooperative outcomes are special cases of the outcomes with endogenous formation of an agreement. That is, when $s = n$, the problem reduces to the full-cooperative solution ($x_s = x_c$ and $z_s = z_c$), while when $s = 1$, it reduces to the pure non-cooperative solution ($x_s = x_{nc}$ and $z_s = z_{nc}$).

The fact that a signatory pollutes less in term of GHG emissions than a non-signatory is not new when cooperation is partial. Cooperation aims at this result. Though, and contrary to a non-signatory, a country which signs the agreement only takes into account the negative externality the others signatories bear because of its emissions. A more remarkable thing relative to the non-cooperative outcome is that, the cooperation between a subgroup of countries also leads the non-signatories to reduce their emission levels. The free-riding phenomenon thus takes a different form as postulated before in the literature: instead of canceling the efforts provided by the cooperating countries, a country which free-rides will abate its emissions but less than a signatory. When payoffs exhibit strategic complementarities, a signatory reduces more its GHG emissions than a non-signatory; and the larger is the number of signatories, the higher the individual abatement efforts of both type of country. Though, the larger is s, the lower the global emissions.

The second point is a consequence of the first one. All countries suffer the same damage: global emissions are the same for all; but a signatory in reducing more its emissions has lower benefits than a non-signatory. Consequently, a country which signs the agreement will always earn less than a country which does not. We can also show that this difference in payoff is decreasing with the size of the IEA. In other words, the larger the number of cooperating countries, the lower is the relative difference between a signatory and a non-signatory payoff.

Contrary to the results established earlier in the literature, we find that signatories as non-signatories reduce their GHG emissions. The effort of the coalition is not anymore (partly) cancelled by the decisions of the non-cooperating countries. However, a non-signatory will always have a higher welfare than a signatory. Under these conditions, the question is then what is the size of the stable IEA?

4.2. The size of stable IEAs with strategic complementarities

To determine how many countries will sign the agreement and how many will not in the first stage, we use the concept of internal and external stability. An IEA is said to be internally stable if none of its members wants to leave; on the opposite, an IEA is externally stable if none of the outsiders wants to join it. Formally, $s*$ is an equilibrium participation level if it satisfies:

$$f_s(s*) \geq f_{ns}(s*-1) \text{ and } f_{ns}(s*) \geq f_s(s*+1).$$

As Diamantoudi and al. (2006), we are interested in determining analytically the size of the stable agreement. In equalizing $f_{ns}(s-1)$ and $f_s(s)$, and allowing s to take non-integer values, it provides an analytical solution $\tilde{s}$. But we are interested in determining the largest integer $s^* \leq \tilde{s}$, such that it satisfies the internal and the external stability conditions (not necessarily with equality).

Formally, we are looking for $s^* \leq \tilde{s}$ such that $f_{ns}(\tilde{s}-1) - f_s(\tilde{s}) = 0$. We find the following solution:

$$\tilde{s} = \frac{-\gamma^4 + \gamma^2(2n+5) - (n+1) + \sqrt{\Delta m}}{2(2\gamma^2 - 1)},$$

With $\Delta m = [-\gamma^4 + \gamma^2(2n+5) - (n+1)]^2 - 4(1-2\gamma^2)[3\gamma^4 - \gamma^2(3+4n) + n - 2] > 0$.

The fifth result establishes the variations in the equilibrium number of signatories with respect to the number of countries concerned with the environmental problem and the perception they have of its seriousness.

Result 5:

Under our assumptions, there exists a unique stable IEA whose size only depends on n and γ:

(i) For any γ and $n = 2$, both countries are always better off in cooperating;

(ii) For $n \geq 3$, if $\gamma^2 \to n$ (the most favourable condition), the stable coalition s^* gets together between 50% and 75% of the countries concerned with the environmental problem; the larger is n, the most s* tends toward 50% of the countries.

(iii) For $n \geq 3$, if $\gamma^2 \to 4n$ (the perception of damages is very strong with respect to the perception of benefits), the stable coalition brings together only two or three countries.

The stable agreement is the larger when the perception of damages is as low as possible. It also corresponds to the case in which countries pollute the most when there is no cooperation. When $\gamma^2 \to n$ cooperation is required (I_1 is the biggest) and is established. Cooperation will always bring together more than half of the countries. Nonetheless it stays partial in the sense that beyond s^*, it pays more to be a non-signatory than a signatory. It becomes too costly to reduce its emissions as much as the signatories.

Given n, the stronger the parameter γ, the lower will be the equilibrium number of signatories. It can be explain by the fact that when policies are unilateral, the stronger is the perception of damages relative to benefits of emissions, the lower will be the individual emission level. Hence, cooperation is less attractive and the size of the stable agreement is smaller.

The last result establishes the environmental impact, in term of global emissions, of the cooperation between a subgroup of countries:

Result 6:

Under our assumptions, we show the following points:

(i) As soon as $\gamma^2 < n + \frac{s^2 - 1}{s}$, the environmental impact of the coalition is increasing in its size;

(ii) Beyond this threshold, the environmental impact of the coalition is decreasing in its size.

If a subgroup of countries agrees to reduce their individual emissions, global emissions will decrease relative to the non-cooperative situation and all countries will gain of such a thing. In the most favourable case, cooperation can lead to a cut off of global emissions of 50%. However, the perception of damages with respect to the benefits of emissions must be below some level for the cooperation (even if partial) to have a real impact. If it is, we show that the reduction of global emissions relative to the non-cooperative case is increasing in the size of the coalition. When γ is beyond the threshold above-defined, the reverse result hold and the environmental impact of the stable coalition decrease with the equilibrium number of signatories.

Depending on the parameter γ, this last result illustrates the cases when cooperation is needed and the cases when it is not. The institutions intended to address international problems then also vary: *"Full cooperation is almost always desirable but rarely essential to the supply of environmental public goods"* (Barrett, 2005).

5. Conclusions

The results obtained under weak strategic complementarities between countries are a lot more optimistic than those observed still now in the literature (using the same game). In assuming that the efforts in abatement of a subset of countries are not partially cancelled by the countries outside, we show that a stable agreement exists and it can set together more than four countries.

Moreover, this coalition improves substantially the situation in view of unilateral policies. In implementing cooperation, the subgroup of countries also incites the non-signatories to abate their emissions.

When environmental damages are perceived very seriously, cooperation and its impact are very low. This phenomenon is explained by the fact that individual emissions already tend toward the incompressible emission levels. Even if countries would decide to cooperate they could not abate below this threshold.

With respect to the previous models, free riding is considered as the most important hindrance to international environmental cooperation. But, in postulating that countries' strategies are substitute, this kind of behaviour is over weighting, yielding to a very low level of cooperation even in the most serious situations.

When countries exhibit strategic complementarities, the free rider incentives always exist in the sense that it's not the grand coalition that forms but an intermediate agreement. However, free-riding takes the form of a less important effort of abatement from non-signatories with respect to the effort of signatories.

6. Appendix

The proofs of result 1, 2, 4 and 6 can be established by differentiation.

Proof result 1:

Differentiating the payoff function with respect to x and y, we find that countries' strategies exhibit complementarities:

$$\frac{\partial^2 f(x,y)}{\partial x \partial y} = \frac{c}{4}(x+y)^{-3/2} > 0$$

Under our assumptions, the payoff function is concave which imply continuity of the best-response function of each country. Moreover, the slope of the latter is always less than one on the feasible strategies' space:

$$\frac{\partial x(y)}{\partial y} = \frac{1}{\gamma^2 - 1} < 1$$

Thus, it will cut only once the first axis and the equilibrium emission level for one country is unique. Finally, in differentiating x_{nc} and z_{nc} with respect to *n* and γ, we find:

$$\frac{\partial x_{nc}}{\partial n} = \frac{\gamma^2}{(\gamma^2 - n)^2} > 0\,;$$

$$\frac{\partial z_{nc}}{\partial n} = \frac{\gamma^4}{(\gamma^2 - n)^2} > 0\,;$$

$$\frac{\partial x_{nc}}{\partial \gamma} = \frac{-2\gamma n}{(\gamma^2 - n)^2} < 0\,;$$

$$\frac{\partial z_{nc}}{\partial \gamma} = n\frac{\partial x_{nc}}{\partial \gamma} < 0$$

Similarly, the proof of the last point is established by differentiating f_{nc} with respect to n and γ.

$$\frac{\partial f_{nc}}{\partial n} = \frac{b\gamma^2(1-\gamma^2)}{2n^{1/2}(\gamma^2 - n)^{3/2}} < 0$$

$$\frac{\partial f_{nc}}{\partial \gamma} = \frac{\gamma b n^{1/2}(-\gamma^2 + 2n - 1)}{(\gamma^2 - n)^{3/2}} < 0$$

Proof result 2:

In the full cooperative case, we find that:

$$\frac{\partial x_c}{\partial n} < 0\,;\ \frac{\partial z_c}{\partial n} > 0\,;\ \frac{\partial x_c}{\partial \gamma} < 0\,;\ \frac{\partial z_c}{\partial \gamma} < 0\,;$$

And,

$$\frac{\partial f_c}{\partial n} < 0\,;\ \frac{\partial f_c}{\partial \gamma} < 0\,\cdot$$

Proof result 3:

To establish the first point we compute:

$$x_c - x_{nc} = \frac{\gamma^2(1-n^2)}{(n\gamma^2 - 1)(\gamma^2 - n)} < 0 \text{ and } z_c - z_{nc} = n(x_c - x_{nc}) < 0\,;$$

Then, being a signatory or a non-signatory, the damages a country bears is the same. Hence, $f_c > f_{nc}$ is evident from the preceding point;

For the last point we find: $\frac{\partial I_1}{\partial n} > 0\,;\ \frac{\partial I_1}{\partial \gamma} < 0\,;\ \frac{\partial I_2}{\partial n} < 0\,;\ \frac{\partial I_2}{\partial \gamma} > 0\,\cdot$

Proof result 4:

Similarly to the first point of the proof of result 3, we compute:

$$x_s - x_{ns} = \frac{n(1-s^2)}{s^2(\gamma^2 - n + s) - s} < 0$$

$$x_{nc} - x_{ns} = \frac{n(s^2-1)}{(s(\gamma^2 - n + s) - 1)(\gamma^2 - n)} > 0$$

The inequality $f_s < f_{ns}$ is straightforward.

For the both last points, we find:

$$\frac{\partial x_s}{\partial s} < 0\,;\ \frac{\partial x_{ns}}{\partial s} < 0\,;\ \frac{\partial z_T}{\partial s} < 0 \text{ and } \frac{\partial f_s}{\partial s} > 0\,;\ \frac{\partial f_{ns}}{\partial s} > 0$$

BIBLIOGRAPHY

Aranson, A. L. (1993). "From 'cooperator's loss' to cooperative gain: negotiating greenhouse gas abatement", *The Yale Law Journal*, 102, 2143-2175.

D'Aspremont, C. A., Jacquemin, J., Gabszeweitz, J. and Weymark, J.A. (1983). "On the stability of collusive price leadership", *Canadian Journal of Economics*,16, 17–25.

Barrett, S. (1994). **"**Self-enforcing international environmental agreements", *Oxford Economic Papers*, 46, 878–894.

Barrett, S. (1997). "The strategy of trade sanctions in international environmental agreements", *Resource & Energy Economics*, 19, 345-362.

Barrett, S. (2003). *Environment and Statecraft: The strategy of Environmental Treaty-Making*, Oxford University Press, Oxford.

.

Barrett, S. (2005). "The Theory of International Environmental Agreements", in *Handbook of Environmental Economics*, Vol. 3. *Economywide and International Environmental Issues*, Amsterdam and San Diego: North-Holland, Elsevier, 1457-1516.

Bauer, A. (1992). "International cooperation over greenhouse gas abatement", Seminar für empirische Wirtschaftsforschung, University of Munich, mineo.

Carraro, C.and Siniscalco, D. (1992). "Transfers and commitments in international negotiations", in K.G. Maler (ed.), International *environmental problems: An economic perspective*, Kluwer Academic Publishers, Dordrecht.

Carraro, C.and Siniscalco, D. (1993). "Strategy for the international protection of the environment", *Journal of public Economics*, 52, 309-328.

Carraro, C. and Marchiori, C. (2002). "Stable Coalitions", Nota di Lavoro FEEM 05.02.

Chander, P. and Tulkens, H. (1996). "The core of an economy with multilateral environmental externalities", *International Journal of Game Theory*, 26, 379-402.

Diamantoudi, E. and Sartzetakis, E. (2006). "Stable international environmental agreements: an analytical approach", *Journal of Public Economic Theory*, 8, 247–263.

Endres, A. (1997). "Increasing environmental awareness to protect the global commons: a curmudgeon's view", *Kyklos*, 50, 3-27.

Finus, M. (2001). "Finite dynamic games with continuous strategy space", in Finus (ed.), *Game theory and international environmental cooperation*, *New horizons in environmental economics*, Edward Elgar, 149-175.

Finus, M. and Rundshagen, B. (1998). "Toward a Positive Theory of Coalition Formation and Endogenous Instrumental Choice in Global Pollution Control", *Public Choice*, 96, 145-86.

Finus, M. and Rundshagen, B. (2003). "Endogenous Coalition Formation in Global Pollution Control: A Partition Function Approach", The endogenous formation of economic coalitions 2003, FEEM Series on Economics and the Environment, 199-243.

Heal, G. (1993). "Formation of international environmental agreements", in Carraro, C. (ed.), *Trade Innovation, Environment*, Kluwer, Dordrecht.

Hoel, M. (1992). "International environment conventions: the case of uniform reductions of emissions", *Environmental and Resource Economics*, 2, 141-159;

Mitchell, R. B. 2002-2007. "International Environmental Agreements Database Project" (Version 2007.1), Available at: http://iea.uoregon.edu/. Date accessed: 11 April 2008.

Rotillon, G., Tazdait, T.; Zeghni, S. (1996). "Bilateral or multilateral bargaining in the face of global environmental change?", *Ecological Economics*, 18, 177-188.

Documents de Recherche parus en 2009[1]

DR n°2009 - 01_ : Cécile BAZART and Michael PICKHARDT
« Fighting Income Tax Evasion with Positive Rewards: Experimental Evidence »

DR n°2009 - 02_ : Brice MAGDALOU, Dimitri DUBOIS, Phu NGUYEN-VAN
« Risk and Inequality Aversion in Social Dilemmas »

DR n°2009 - 03_ : Alain JEAN-MARIE, Mabel TIDBALL, Michel MOREAUX, Katrin ERDLENBRUCH
« The Renewable Resource Management Nexus : Impulse versus Continuous Harvesting Policies »

DR n°2009 - 04_ : Mélanie HEUGUES
« International Environmental Cooperation : A New Eye on the Greenhouse Gases Emissions' Control »

[1] La liste intégrale des Documents de Travail du LAMETA parus depuis 1997 est disponible sur le site internet : http://www.lameta.univ-montp1.fr

Contact :

Stéphane MUSSARD : mussard@lameta.univ-montp1.fr